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Changes in Herbicide Use after Adoption of HR Canola in Western Canada

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This article examines the changes in herbicide use in relation to canola production in Western Canada, comparing 1995 and 2006. The commercialization and widespread adoption of herbicide-resistant (HR) canola has changed weed management practices in Western Canada. Before the introduction of HR canola, weeds were controlled by herbicides and tillage as the leading herbicides at that time required tillage to allow for soil incorporation of the herbicide. Much of the tillage associated with HR canola production has been eliminated as 64% of producers are now using zero or minimum tillage as their preferred form of crop and soil management. Additionally, there have been significant changes regarding the use and application of herbicides for weed control in canola. This research shows that when comparing canola production in 1995 and 2006, the environmental impact of herbicides applied to canola decreased 53%, producer exposure to chemicals decreased 56%, and quantity of active ingredient applied decreased 1.3 million kg. The cumulative environmental impact was reduced almost 50% with the use of HR herbicides. If HR canola had not been developed and Canadian canola farmers continued to use previous production technologies, the amount of active ingredient applied to control weeds in 2007 would have been 60% above what was actually applied.

Nomenclature: 2,4-D; clopyralid; ethalfluralin; ethametsulfuron; glufosinate; glyphosate; imazamox; imazethapyr; sethoxydim; trifluralin; *Brassica napus* L.

Key words: Genetic modification, chemical toxicity, environmental impact quotient, active ingredient, land management practices.

Este artículo examina los cambios en el uso de herbicidas en relación a la producción de canola en el occidente de Canadá comparando 1995 y 2006. La comercialización y la amplia adopción de canola resistente a herbicidas han cambiado las prácticas de manejo de las malezas en el occidente de Canadá. Antes de la introducción de la canola resistente a herbicida, las malezas se controlaban por medio de herbicidas y labranza, ya que el herbicida principal requería la labranza para permitir la incorporación del herbicida al suelo. La mayoría de la labranza asociada a la producción de canola resistente a herbicida ha sido eliminada debido a que 64% de los productores prefieren usar labranza cero o mínima para el manejo del cultivo y del suelo. Adicionalmente, ha habido cambios significativos en referencia al uso y aplicación de herbicidas para el control de malezas en la producción de canola. Esta investigación muestra que cuando se compara la producción de canola en 1995 y 2006, el impacto ambiental de los herbicidas aplicados a la canola disminuyó 53%, la exposición de los productores a los químicos disminuyó 56% y la cantidad de ingrediente activo aplicado se redujo en 1.3 millones de kilogramos. El impacto ambiental acumulativo fue casi 50% menos con el uso de canola resistente a herbicidas. Si la canola resistente a herbicidas no hubiera sido desarrollada y los agricultores canadienses de este cultivo continuaran utilizando la tecnología previa de producción, la cantidad de ingrediente activo aplicado para el control de malezas en 2007 hubiera sido 60% más de lo que actualmente se aplicó.

Herbicide-resistant (HR) canola has been developed to provide superior weed control with herbicides that would normally injure or kill canola. Unrestricted commercialization began in 1997 with an adoption rate, by Western Canadian farmers, of 25% (Smyth et al. 2011). By 2004, adoption was 98%. The rate of adoption has been above 95% ever since. Over this period herbicide use patterns changed dramatically—herbicides that were the minority of applications in 1995 have become the dominant herbicides applied in 2006. The herbicides now widely used are significantly less toxic to farmers and the environment.

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For the 2005 and 2006 crop years, farmers reported that 48% of their acreage used glyphosate-resistant varieties, 37% used glufosinate-resistant varieties, and 10% used imidazoline-resistant varieties. These adoption rates are consistent with the adoption rates provided by the canola industry, which identifies glyphosate-resistant market share at 44%, glufosinate-resistant at 40%, and imidazoline-resistant at 11% (Chris Anderson, personal communication).

The focus of this research is to compare the environmental impact of the herbicides being presently applied relative to the environmental impact of the herbicides that were applied to canola before the introduction of HR canola. This study compares canola production in 1995 and 2006. Canola production in 1995 and 2006 was virtually identical, with 5.25 million ha cultivated in 1995 and 5.21 million ha in 2006 (Canola Council of Canada 2009).

Before the introduction of HR canola, producers in Western Canada had to select fields to plant to canola that, in terms of weed populations, were deemed to be "the

Table 1. Recent studies on herbicide-resistant (HR) crops.

Research study	Crop type and country	Study reference period	Change in herbicide application	Environmental impact
Canola Council of Canada 2001	HR canola in Canada	1999/2000	Aggregate 40% decrease	NA[b]
Brimner et al. 2005[a]	Canola in Canada	1995–2000	20% decrease	37% decrease
Kleter et al. 2007[a]	Canola in the United States	2004 crop year	30% decrease	42% decrease
Brookes & Barfoot 2010[a]	Canola in Canada and the United States	1996–2008	8% decrease	16% decrease
Leeson et al. 2006	Canola in Canada	1995–2003	12% decrease	22% decrease

[a] Peer-reviewed publication.

[b] Abbreviation: NA, not applicable.

cleanest." This was at least partly because herbicide weed control options were limited because of the lack of selective herbicides suitable for use in canola. Most herbicides for canola had to be soil incorporated before seeding and many of these chemicals had residual second-year effects that restricted cropping options in the subsequent year. This pattern has now been completely reversed as producers are able to select any field, but reportedly choose, in terms of weed populations, "the dirtiest" field to seed to canola. Herbicide weed control options have changed so much that producers are able to use HR canola to create fields that are very clean in terms of weed populations, so that at times no herbicides are required to control weed populations in succeeding crops. This study examines the toxicological effects of that change.

Comparing herbicides and their toxicity is not a simple process. Each herbicide used in agriculture has different environmental impacts and the application rate of each herbicide varies, making direct comparisons between two or more herbicides very challenging. In an attempt to establish the opportunity to undertake herbicide comparisons, Kovach et al. (1992) developed the environmental impact quotient (EIQ), which measures the relative toxicity of chemicals. The EIQ is comprised of effects on three separate targets: the ecological environment, farm workers, and consumers. The EIQ is regularly updated to take into account new toxicity impact studies and newly available herbicides, providing a consistent tool for comparing different herbicides. By using these measures and applying them to actual farm practices, one can determine which form of agricultural crop production has the lowest impact on the environment, farmers, and consumers.

The main limitation of using the EIQ model to assess changes in chemical applications to large-scale crop production is that when it was developed in the early 1990s it was designed to assist in exploring the environmental impacts of changes in agriculture chemical use as part of integrated pest management system development in the fruit and vegetable sector (Kovach et al. 1992). Although we and others have used the EIQ to explore the environmental impact of different cropping systems, including conventional and biotechnology-based agriculture, the EIQ was not specifically developed to evaluate large-area crops. The EIQ is better than assessments that only consider the active ingredient, but is still a rough measure of impacts on the environment when applied to large-scale agriculture.

The EIQ utilizes a five-point ordinal scale to indicate the relative toxicity of chemicals, where one is least toxic or least harmful and five is the most toxic or most harmful. The farm worker component is comprised of the effects on the applicator and the picker. This latter impact is more relevant to fruit and vegetable production than it is to large-scale canola production in Western Canada, where harvesting is highly mechanized. The consumer component is comprised of the direct consumer effects from consumption and the impact of residue in the groundwater. Given that consumers only rarely directly consume unprocessed canola (most of the seed is crushed and refined into canola oil and the meal is fed to animals), this aspect of the EIQ in our study focuses predominantly on groundwater effects. The ecological component is comprised of aquatic and terrestrial effects, which includes assessments of chemicals on fish, birds, bees, and beneficial arthropods.

Herbicides have a range of toxicological impacts and exhibit both acute and chronic toxicity. Acute toxicity measures the short-term poisoning potential of the organism. A value of exposure is assigned when an amount of material is given all at once to a group of test subjects that results in half of the test population expiring—this is called the lethal dose 50, or LD_{50}. For chronic toxicity no numerical value is assigned; the chemical is annotated as presenting "no effect," "may affect," and "does cause."

Within the literature (Table 1) there is a consensus that the amount of active ingredient per hectare has decreased, herbicides are applied at lower rates, and that producer exposure has been reduced. Total usage varies, depending on which crops are being planted. For, example, although the total area allocated to canola in Western Canada was virtually the same in 1995 and 2006, there was significant volatility in production in response to the expected relative price of canola and other crops. The data from 2008 show an unprecedented sixth consecutive year of increase in canola production, rising to 6.47 million ha. As the number of canola hectares increases over the reference level of approximately 5.22 million ha, the total volume of chemicals applied to canola crops has correspondingly increased, but this has been offset somewhat with reduced chemical usage at the per-hectare scale.

The first HR/non-HR canola comparison done in Canada was based on data from 1999–2000. The Canola Council of Canada (2001) commissioned a study to assess the agronomic and economic impacts of transgenic canola. At that time, approximately three-quarters of the canola was produced using HR varieties. Herbicide input costs were examined, focusing on fields that had been left as summer fallow in 1999 (where some farmers made chemical applications to the summer fallow field) and were then sown to canola in 2000. The average per-hectare cost over the 2-yr period was Can$33.79 for HR canola and Can$55.65 for non-HR canola. The study estimates the lower cost of herbicide use on

HR canola fields to be the equivalent of 6,000 fewer tonnes of herbicide application by volume in 2000.

Brimner et al. (2005) used Kovach's method to examine the changes in herbicide use due to HR canola adoption between 1995 and 2000. They found that herbicide use on conventional canola had increased by 30%, whereas herbicide use on HR canola had decreased by 20%. In terms of the EI of HR canola, a 37% decrease was observed, whereas the EI of conventional canola increased 56%. The authors reported that they faced some challenges in determining herbicide use. They assumed that HR canola was only sprayed with a corresponding herbicide and that no other herbicides were tank mixed, thus potentially underestimating the actual application rate. Conversely, they may have overestimated herbicide application to HR canola if one of the relevant herbicides was applied to conventional canola fields as a burn-off before seeding. Although the authors acknowledge that the potential exists for either over- or underestimation of herbicide application, there is no prima facie evidence to indicate whether either is likely. Thus, there is no reason to reject these results; they will be used as the benchmark for comparison purposes in this study.

Beckie et al. (2006) examined the first decade of HR crop use in Canada and noted that, before the introduction of HR canola, herbicide options for canola were limited. The most common herbicide application method included soil incorporation, which had a low efficacy rate and the residual activity of some herbicides resulted in crop rotation restrictions in the subsequent year. Leeson et al. (2006) examined trends in herbicide use in canola production through the use of a series of weed surveys. The authors compared the results of weed surveys from the three Prairie provinces from 1995 to 1997 against similar surveys from 2001 to 2003. They found a 12% reduction in herbicide use and an EI drop of 22% per hectare.

A review study by Kleter et al. (2007) compared conventional and transgenic canola crops in the United States over 4 yr. The authors estimate that the application of pesticide active ingredient was 30% lower in HR canola than in conventional canola crops. The total EI per hectare was 42% lower, the ecological impact was 39% lower, and the farmer impact was 54% lower.

Brookes and Barfoot (2010) used the EIQ methodology to compute and compare EIQ values for conventional and biotech crops, aggregating these data to a national level. Their research provided an analysis of the changes in herbicide use between 1996 and 2008. In their analysis of HR canola in North America, they found that the EI decreased by 24%. The amount of active ingredient applied to canola decreased by 13.74 million kg or 18%. The study assumed that the highest application rate was used in all instances, which created the potential for an overestimation of active ingredient application, thus underestimating the decline in usage and the net overall benefit.

Sydorovych and Marra (2008) estimated that the aggregate welfare impact from the reduced risk of herbicides in 2001 for U.S. soybean farmers was US$90 million. This estimate is based on three valuations of risk: reduced acute health risk, reduced chronic health risk, and reduced surface water runoff.

As the adoption of transgenic crops passes the first decade, there is a small but growing body of literature that evaluates herbicide application and the EI of the application of these herbicides. Not all of the above studies focus specifically on the adoption and production of HR canola, but those that do seem to generally illustrate a substantial reduction in herbicide use and considerably lower environmental impacts.

Methodology and Demographics

Canola herbicide use data for the Western Canada 2006 crop year was gathered through a survey conducted in spring 2007 by researchers at the University of Saskatchewan.[1] These data were collected through a four-page, 80-question survey that was developed and distributed to agricultural producers. The survey was comprised of six major areas of focus: weed control; volunteer canola control; canola production history; specific weed control measures on canola fields and subsequent crops; crop and liability insurance; and general demographics. Open, closed, and partially open questions were asked in the survey. Space was provided to enable producers to more fully explain changes within the production system to facilitate a more complete understanding of producer choices. Where a quantification of producer attitudes was required, a simple three-point scale was used, which allowed for positive, neutral, and negative responses.

This survey gathered detailed information on weed-control methods, the suite of herbicides used, application rates, hectares treated, and the number of applications. This information was used to identify the top five herbicides applied to canola in 2006. The application of the top five herbicides represented over 95% of the herbicide applications made to canola in that year. These data were used to calculate the potential toxic effects on Western Canadian farmers and consumers and the ecological impacts of these herbicides. Comparisons are made between the herbicides that were used before adoption of HR canola and those reported in 2006. On the basis of this comparison, it is possible to identify the toxicology changes that have occurred after the first decade of HR canola production and to quantify the impact of these changes.

Forty thousand surveys were distributed across the three Prairie provinces in March and April 2007. Distribution of the survey was through Canada Post's unaddressed ad-mail service providing a cluster sampling method. See Figure 1 for responses by rural municipality across the various ecoregions.

In total, 685 surveys were received, with 571 meeting our population criteria. Outliers within the database were identified and removed utilizing the box-plot method as developed by Tukey (1977) and outlined by NIST/SEMATECH (2006). Extreme outliers, or upper outliers, were identified on the basis of the amount of hectares treated by the herbicide. Table 2 outlines the distribution of usable responses across the three Prairie provinces and between areas of low and high canola production. Although the number of respondents relative to the number of surveys distributed indicates a low response rate (1.71%), it is important to note that the Canada Post's unaddressed ad-mail service delivers

[1] The herbicide use data were collected for the entire growing season and have not been differentiated into preseeding burn-off, post-emergence application, or preharvest perennial weed control.

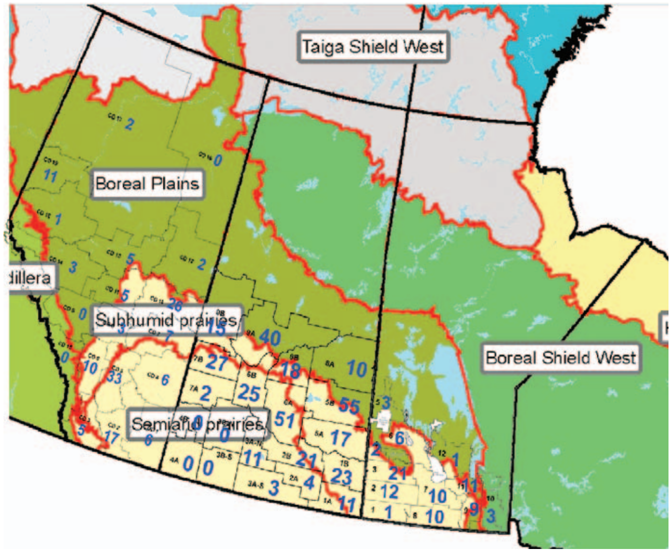

Figure 1. Survey responses from various ecoregions of Canada.

Table 2. The distribution of usable survey responses ($n = 571$).

	Low production[a]	High production[b]	Total
Alberta	14%	11%	25%
Manitoba	NA[c]	16%	16%
Saskatchewan	32%	27%	59%
Total	46%	54%	100%

[a] Areas of the provinces that, on the basis of statistical production data, have lower-than-average canola production.

[b] Areas of the provinces that, on the basis of statistical production data, have higher-than-average canola production. Because of the smaller area of crop production in Manitoba, the province is treated as being entirely in the high-production area.

[c] Abbreviation: NA, not applicable.

surveys to all mail addresses within the identified region. There is no way to know how many households received surveys that were not farmers or did not produce canola. Therefore, the actual response rate is unknown and is most certainly greater than what can be calculated here. The important point is that demographically, our respondents are very representative of the national agriculture census data.

The demographics of the sample population are similar to the source population as reported in the Statistics Canada (2006) Farm Census (Table 3). The average age of farmers is 52 in Saskatchewan and Alberta, and 51 in Manitoba. Our survey population has a substantially higher level of postsecondary education, where the census data identify the percentage of producers with a university degree in Manitoba at 8%, Saskatchewan at 8%, and Alberta at 9%.[2] Average farm size of the sample population was greater than that of census data, where the average Alberta farm size was 669 ha, Saskatchewan 705 ha, and Manitoba 549 ha.

The respondents to this survey had relatively large operations (670 ha), with, on average, over one-quarter of their operation dedicated to canola (Table 3). The average respondent has farmed for 30 yr. These producers reported growing canola for an average 20 yr and adopting HR canola first in 1999; on average they reported that they removed conventional canola varieties from their crop rotations by 2000.

Application of EIQ Method

As discussed above, the EIQ method developed by Kovach et al. (1992) is compartmentalized in nature, allowing for herbicide impacts to be assessed for each of the three targets. Although it is important to provide EIQ values to allow for herbicide comparisons, it is also valuable to provide the EIQ subcomponent values to appreciate the relative impacts on each of the three targets. Given the nature of canola production and the lack of direct consumer consumption of whole canola seeds, the subcomponents of greater interest are the farm workers and ecological effects.

The environmental impact quotient for farm workers (EIQ_f) measures the effects of herbicide application as a function of acute toxicity (DT), chronic toxicity (C), and plant surface half-life (P).

$$EIQ_f = C(DT \times 5) + C(DT \times P)$$

The farmworker component of the EIQ is made up of two parts, the applicator and the picker effects. The applicator effect is the exposure of the farmworker when herbicides are being applied to the crop. The applicator effect is a function of acute toxicity (in terms of dermal toxicity), multiplied by the chronic toxicity of the herbicide. Because farmworkers directly handle herbicides, it is granted a weight of five to reflect the severity of this exposure. The picker effect in relation to canola production is the herbicide residues that still exist on the crop at harvest. Canola harvesting in Western Canada is highly mechanized, which significantly reduces the direct contact between farmworkers and the crop. Harvesting does, however, expose the farmworker to dust and debris

[2] The number of respondents with a university degree is substantially higher in Saskatchewan than is reflected in the census data. A variety of factors contributes to this. The farm size is larger than average and producers are slightly younger than the average, which tend to be correlated with higher levels of education. Moreover, the affiliation of this research with the University of Saskatchewan may have triggered a greater response from graduates than from others.

Table 3. The demographics of survey participants by province. Census data were extrapolated from Statistics Canada (2006).

	Alberta	Saskatchewan	Manitoba	Total/ave.
Number of respondents to survey	144	335	92	571
Average age				
Sample	45–54	45–54	45–54	45–54
Census	52	52	51	52
University degree				
Sample	14%	21%	7%	14%
Census	9%	8%	8%	8%
Average farm size (hectares)				
Sample	669	705	549	670
Census	427	589	405	473
Average canola hectares	205	193	162	190
Average years experience with canola	19.3	20.6	20.8	20.3
First year with herbicide-resistant canola	1999	1999	1998	1999

Table 4. Tillage operations and herbicide-resistant canola systems in 2006.

Tillage method	Imidazoline-resistant (n = 40)	Glufosinate-resistant (n = 135)	Glyphosate-resistant (n = 154)	Average (n = 340)
Zero-till	60%	53%	51%	54%
Cultivation	23%	20%	24%	22%
Harrow (min-till)	13%	12%	10%	11%
Cultivation and harrow	5%	15%	16%	14%

dispersed into the air as a result of the swathing and threshing processes. Again, chronic and acute toxicity are used along with the persistence of the herbicide on the plant material, reflected by the plant surface half-life. The value of the EIQ_f can range from 6 (the least toxic) to 250 (the most toxic).

The EIQ_f determines a toxicity value for one unit of herbicide application. Because herbicides are not applied at the same rate, measuring the amount of active ingredient applied cannot be used as a direct comparison between herbicides. Measuring the environmental impact to farmworkers (EI_f) is calculated by multiplying the EIQ_f by the application rate and by the area that is sprayed.

$$EI_f = EIQ_f \times \left[\sum (\text{Area}_i \times \text{Rate}_i \times \text{Pass}_i) \Big/ \sum \text{Area}_i\right] \quad \text{for } i = 1 \ldots n$$

The EI_f for the benchmark year (1995) has been estimated from previous data (Kovach et al. 1992) and this value is compared with 2006, where we have detailed data on application rates and the area sprayed. The 2006 application rate was calculated using a weighted average for the number of hectares sprayed, producing an average per hectare rate used by farmers. This average more accurately reflects the amount of herbicide applied to each hectare of land, compared with the average application rate for each field. Herbicides containing the same active ingredient but in different concentrations were accounted for by attributing the corresponding amount of active ingredient per herbicide to the average per hectare rate. This was done to provide a more accurate representation of the amount of active ingredient applied. Some areas were treated with herbicides containing more than one active ingredient (i.e., tank mixes), requiring additional attributions of each active ingredient applied to the appropriate fields.

The EIQ values were then calculated for the other two subcomponents. The environmental impact quotient for consumers (EIQ_c) is the sum of the potential for consumer exposure and the potential for groundwater effects. Consumer exposure is determined by C multiplied by the average of chemical residue potential in soils (S) and on P, multiplied by the systematic potential (SY) or the pesticide's ability to be absorbed by the plant. Groundwater effects (L) measure the potential of the pesticide to leach into consumer drinking water reservoirs and are added to the exposure to determine the EIQ_c.

$$EIQ_c = \{C[(S+P)/2] \times SY\} + L$$

The environmental impact quotient for the ecological component (EIQ_e) is a combination of the aquatic and terrestrial effects of chemicals. The effects on fish are measured as the toxicity to fish (F) multiplied by the potential for surface runoff (R). The impact on birds is a measurement of chemical toxicity to birds (D) times the average half-life of chemicals on S and P, multiplied by a factor of three. Impacts on bees are measured as bee toxicity (Z) multiplied by plant surface half-life (P) multiplied by a factor of three. Impacts on beneficial arthropods are measured by beneficial arthropod toxicity (B) multiplied by plant surface half-life (P) multiplied by a factor of five. The terrestrial impacts are multiplied by a factor of three because, according to Kovach et al. (1992), the potential for direct exposure effect is higher than it would be for aquatic life. Arthropod exposure is adjusted by a factor of five because these organisms can spend their entire lives within a crop, whereas birds and bees are considered to be more transitory.

$$EIQ_e = (F \times R) + \{D \times [(S+P)/2] \times 3\} + (Z \times P \times 3) + (B \times P \times 5)$$

The total EIQ value is then the sum of the three subcomponent values, divided by three.

$$EIQ = (EIQ_f + EIQ_c + EIQ_e)/3$$

To make comparisons between herbicides on the consumer and ecology subcomponents we use the same format as used for farmworkers, that is, the specific EIQ subcomponent value is multiplied by the area of herbicide application and the application rate.

$$EI_c = EIQ_c \times \text{Area} \times \text{Rate}$$

$$EI_e = EIQ_e \times \text{Area} \times \text{Rate}$$

The following section provides the EIQ values, the subcomponent values, and EI values for the herbicides used on conventional canola in 1995 (before the commercialization of HR canola) and for the herbicides used on canola in 2006, when the adoption of HR canola was 95%.

Results and Discussion

Land management practices in Western Canada changed substantially after the adoption of HR canola varieties. When asked about weed management practices, the survey respondents reported that many of them have adopted minimum[3] or zero tillage practices, with 64% of respondents indicating that they use one of these two systems (Table 4). Producers utilizing glyphosate-resistant systems were slightly more likely to conduct tillage operations than other systems. When asked about weed control measures conducted on their 2006 canola

[3] For the purposes of this survey, harrowing is defined as minimum tillage or min-till. Zero tillage is the use of direct seeding methods. Conventional tillage is the continued use of cultivation as the preferred method of weed control.

Table 5. The top five prominent herbicides used in canola in 1995. Values in the table are based on application rate data from Brimner et al. 2005 and EIQ values from Kovach et al. 2009.

Herbicide	EIQ_f[a]	EIQ_c[b]	EIQ_e[c]	EIQ[d]	Grams of ai ha^{-1}	Area applied
Ethalfluralin	15.0	6.0	49.0	23.3	1100	32%
Trifluralin	9.0	5.5	42.0	18.8	800	31%
Clopyralid	8.0	8.0	38.4	18.1	151.2	16%
Sethoxydim	7.1	4.6	51.0	20.9	144	15%
Ethametsulfuron	8.0	6.0	45.6	19.9	15	15%

[a] Environmental impact quotient on farmers and farmworkers.

[b] Environmental impact quotient on consumers.

[c] Environmental impact quotient on the ecology.

[d] Environmental impact quotient.

Table 6. Environmental impacts (EIs) of herbicide use in canola in 1995.

Herbicide	EI_f[a] ha^{-1}	EI_c[b] ha^{-1}	EI_e[c] ha^{-1}	EI ha^{-1}	% of total
Ethalfluralin	16,500	6,600	53,900	25,630	55
Trifluralin	7,200	4,400	33,600	15,040	32
Clopyralid	1,210	1,210	5,806	2,737	6
Sethoxydim	3,010	662	7,344	3,672	6
Ethametsulfuron	120	90	684	299	1
Cumulative impact	26,052	12,962	101,334	47,378	
Percentage of total	19	9	72		100

[a] EI on farmers and farmworkers.

[b] EI on consumers.

[c] EI on the ecology.

crop, 28% of producers reported that they used both herbicides and tillage, with just 7% reporting only tillage. Use of tillage has markedly decreased since 2000, when 89% conducted tillage operations as a form of weed control (Canola Council of Canada 2001). The adoption rate for HR canola at this time was 76%. The movement to minimum or zero tillage operations across Western Canada began to increase in the early to mid-1990s, just before the commercialization of HR canola. We can say with confidence that the diffusion of HR canola increased the adoption of zero or minimum tillage systems. It would appear that these two technologies simultaneously evolved. The adoption of HR canola does appear to allow producers using zero tillage to stay with this land management system as before the commercialization of HR canola, producers using zero tillage would not receive effective and continuous weed control; therefore, they would have to resort to tillage as a means of effective weed control. As well, at this time, herbicides that were used in weed control frequently had to be soil incorporated.

With weed management practices, it is important to investigate how they are related to the use of herbicides as a form of weed control. To be able to make a statistically valid comparison between herbicide application before the commercialization of HR canola and the situation a decade later, we have taken the application area data from Brimner et al. (2005) and the EIQ coefficient values from Kovach et al. (2009) providing us with a representative perspective on the basis of 1995 canola production.[4]

Table 5 shows the estimated total EIQ, the three EIQ subcomponent values, and the grams of active ingredient per quantity applied, assuming the lowest application rate was used. The area of herbicide application exceeds 100% because of tank mixing. The five most common herbicides used with the production of canola in 1995 are included and these five herbicides are reflective of nearly all the herbicides applied to canola at this time.

The subcomponent values of the EIQ, the application rate, and the application area provide the EI to farmworkers, consumers, and the ecology on a per-hectare basis (Table 6). The EI ha^{-1}, which is the sum of the three subcomponents divided by three, allows for direct toxicological comparison between different active ingredients. These results indicate that ecological impacts accounts for about 72% of the cumulative impact of the top five herbicides applied to canola

Table 7. The top five canola herbicides used in 2006 with environmental impact quotient (EIQ) values based on Kovach et al. 2009.

Herbicides	EIQ_f[a]	EIQ_c[b]	EIQ_e[c]	EIQ	Grams of ai ha^{-1}	Area applied
Glyphosate	8.0	5.0	33.0	15.3	697	48%
Glufosinate	12.0	8.0	40.6	20.2	477	12%
Imazamox	8.0	8.0	42.6	19.5	14.7	4%
Imazethapyr	15.6	10.6	32.4	19.6	14.7	4%
2,4-D	24.0	7.0	31.0	20.7	414	2%

[a] EIQ on farmers and farmworkers.

[b] EIQ on consumers.

[c] EIQ on the ecology.

[4] We use the 2009 EIQ coefficients as they are the most accurate and up-to-date data. The coefficients have been revised periodically since 1992 as more information regarding chemical application becomes available. By using the 2009 coefficients we are able to make the most accurate comparison possible between herbicide applications in 1995 and 2006.

Table 8. Environmental impacts (EIs) of herbicide use in canola in 2006.

Herbicide	EI_f^a ha^{-1}	EI_c^b ha^{-1}	EI_e^c ha^{-1}	EI ha^{-1}	% of total
Glyphosate	5,573	3,483	22,988	10,658	36
Glufosinate	5,724	3,816	19,366	9,635	32
Imazamox	118	118	626	287	0.01
Imazethapyr	229	156	476	288	0.01
2,4-D	9,959	2,905	12,864	8,590	29
Cumulative impact	21,603	10,477	56,320	29,458	
Percentage of total	24	12	64		100

[a] EI on farmers and farmworkers.

[b] EI on consumers.

[c] EI on the ecology.

in 1995. The farmworker impact contributed only 19% of the total and, as expected, the consumer impact contributed only about 9%.

The top two herbicides applied to canola in 1995 have significant ecological impacts, given that these two herbicides were applied to 63% of total canola acres. One of the ecological challenges of farmers using trifluralin and ethalfluralin was that it had to be soil incorporated to provide the most effective weed control. As a result of herbicide residues in the soil, options for subsequent crops were restricted.

Comparable data for the top five canola herbicides in 2006 is provided in Table 7.[5] The overall EIQ values for the five chemicals in 2006 are somewhat lower than for the top five chemicals used in 1995. Respondents reported that they applied glyphosate and glufosinate at the rate of 0.70 kg ha^{-1}, which is marginally above the recommended rate for glyphosate (where the upper margin for the recommended rate is 0.69 kg ha^{-1}) and marginally below the recommended rate for glufosinate where the lower margin is 0.20 kg ha^{-1}. A mixture of imazamox and imazethapyr was applied at the recommended rate (42 g ha^{-1}). Insufficient data were available for 2,4-D application rate and was assumed to be the highest recommended rate. Application rates for chemicals can vary from the recommended rates depending on the price of herbicides relative to the density of weeds per square meter, the type of weeds being treated, and the interaction between herbicides in a tank mix and its impact on the weed population.

The amount of active ingredient per hectare dropped substantially between 1995 and 2006. Producers in 2006 applied herbicides that are considerably more benign than those applied in 1995. The lower amount of herbicide active ingredient applied translates into lower EI values (Table 8). In 2006, the two leading herbicides accounted for 86% of the canola acres that were treated. It is interesting to observe that only 70% of respondents report using herbicide.[6] Although applying herbicide to 70% of canola production might seem low, it is not outside of what is normal in crop production. It is not uncommon for producers using tillage as part of their land management practices to get excellent weed control at the time of seeding. In crop seasons with excellent soil moisture and abundant heat, canola germination is rapid, creating a canopy on the field that dramatically limits the number of weeds that are able to emerge and survive after seeding. Therefore, in some years, producers do not need to apply a post-emergence herbicide to control weeds. In the spring of 2006, moisture conditions were listed as excellent for most of the prairies and the temperature was above average (Canadian Wheat Board 2006).

When asked about herbicide applications, 27% of respondents reported no herbicide use, which is higher than the 22% of farmers who reported using cultivation methods (Table 4). There are several possible reasons for this discrepancy. Eight percent of farmers reported that they did not need to spray widely; rather, they had adequate weed control from previous year's cultivation or they may have only spot-sprayed limited parts of a canola field for weed control purposes. Glyphosate can also be used as a burn-off chemical before seeding, which may account for some of the variance between Tables 8 and 4.

The 2006 subcomponent values of the EIQ, the application rate, and the application area provide the EI to farmworkers, consumers, and the ecology on a per-hectare basis (Table 8). These results indicate that ecological impacts accounts for about 64% of the cumulative impact of the top five herbicides applied to canola in 2006. The farmworker impact contributed only 24% of the total and, as expected, the consumer impact contributed only 12%.

The top two herbicides applied to canola in 2006 were applied to 86% of total canola acres. As expected, the EI to farm workers was lower, due to changes in the suite of chemicals in use. In addition, improved safe chemical handling awareness and education programs have further reduced farmer exposure to herbicides.

Comparing the 2006 impacts (postadoption) with the 1995 impacts (preadoption), it becomes evident that there are substantial environmental benefits, associated with changes in herbicide use patterns, from the widespread adoption of HR canola (Table 9).[7] The cumulative EI effect from herbicides

[5] In the review process for this article, it was brought to the authors' attention that the EIQ value for glyphosate as listed in Kovach et al. 2009 was erroneous. The value listed online for glyphosate by Kovach et al. is 25.3. The authors contacted Dr. Kovach by E-mail to confirm the error and to inquire as to the correct value. In an E-mail dated December 12, 2009, Dr. Kovach acknowledges the error and justifies the use of 15.3 as the EIQ value for glyphosate.

[6] As noted by Leeson et al. (2004), in 2003 12% of canola producers did not spray. This figure ranges as high as 17% for barley growers in that year. Some producers only use tillage as their means to control weeds.

[7] The EI and the EI subcomponent values are derived from the data in Tables 5–8. The EI and subcomponent values for 1995 are derived from the values in Table 6 multiplied by the area percentage in Table 5. Conversely, the EI and subcomponent values in Table 8 are multiplied by the area percentage in Table 7.

Table 9. Environmental impact (EI) differences between the top five canola herbicides 1995 and 2006.

Comparison	1995	2006	% change
EI ha^{-1}	13,898	6,467	−53
EI_f^a ha^{-1}	8,176	3,575	−56
EI_c^b ha^{-1}	3,783	2,199	−42
EI_e^c ha^{-1}	29,798	13,659	−54
Grams of ai ha^{-1}	648	401	−38
Total ai (million kg)	3.4	2.1	$(-1.3)^d$

[a] EI on farmers and farmworkers.

[b] EI on consumers.

[c] EI on the ecology.

[d] Difference between 1995 and 2006.

dropped by 53% between the two periods. When the subcomponent values of the EI are compared, there is a reduction of over 40% in each of the subcomponents. The farmworker and ecology subcomponents decline by 56% and 54%, respectively, whereas the consumer subcomponent declines by 42%. Given that the total canola acreage in 1995 and 2006 was virtually identical, the reduction in the EI is almost entirely attributable to the adoption of HR canola. The total volume of herbicide active ingredient applied to canola fields dropped by 1.3 million kg, representing a 38% reduction in quantity between the 2 years.

The lower usage of herbicides for canola production is an important component in affecting the EI of crop production in Western Canada. Whereas total canola acreage held constant in the two reference years in this study, the recent trend has been for production to rise. Canola data from 2008 show an unprecedented sixth consecutive year of increase in canola acreage, rising to over 6 million ha (up from the reference rate of 5 million ha). All other things holding constant, this rise in canola cultivation would have raised herbicide use by about 60%. But the adoption of HR canola and corresponding reduction in application rates of active ingredient more than offset this increase in production. Figure 2 presents the situation assuming HR canola had not been developed.[8] The figure shows that in 2007, 2.56 million kg of active ingredient were applied to canola fields. If HR canola had not been developed and farmers were still using conventional canola varieties, the amount of herbicide applied would have risen to 4.1 million kg of active ingredient.

The adoption of HR canola has substantially affected the EI of herbicide use in Western Canadian agriculture. Farmers have rapidly and aggressively adopted HR canola as a tool to increase the flexibility of weed control. This has contributed to a corresponding shift in the types of herbicides applied to canola, with farmers moving away from soil-incorporated pre-emergent herbicides (such as trifluralin and ethafluralin) to foliar-applied post-emergent herbicides (such as glyphosate and glufosinate). The shift in herbicides has enabled farmers

[8] If HR canola had not been developed, there would have been improvements in canola varieties from conventional breeding techniques. The best comparison of how conventional canola breeding has evolved can be based on European rapeseed breeding, where no HR varieties exist at present. Europe has essentially banned HR technology and the crop varieties developed in Europe offer the best comparison of how plant breeding has developed in the absence of biotechnology.

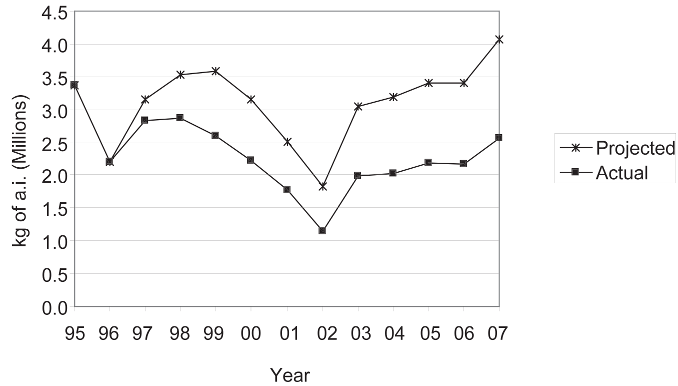

Figure 2. Herbicide application: Actual herbicide-resistant (HR) canola vs. projected without HR canola.

to adopt a more sophisticated approach to weed control, with producers applying herbicide when and where it is needed and at an appropriate rate for the control of observed weed populations.

This study confirms previous findings that the adoption of HR canola and a new suite of herbicides has benefited farmers, the environment, and consumers. The coevolution of zero- and minimum-till land management practices and HR canola have resulted in a cropping system that delivers substantial safety improvements to farmers, citizens, consumers, and the environment.

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